4. Brief History of Tectonism and Structural Elements

Tectonic features can be expected to exert a primary control on the flow system in general and on the initiation of fast paths in particular at Yucca Mountain. These features exist at several scales, ranging from major block-bounding faults with displacements of 100 m or more, to very small discontinuous faults with offsets on the order of centimeters. This section summarizes the different types of faults with respect to their genesis and subsequent growth.

4.1. Structural Elements in the Central Block

The central part of Yucca Mountain that includes the potential repository occupies a relatively undeformed block bounded by major, or block-bounding, faults (Fig.1). Block-bounding faults within the vicinity of this central block of Yucca Mountain include the Solitario Canyon, Bow Ridge, and Dune Wash faults. All of these major faults dip steeply to the west and have cumulative displacements in the range of 100 to 200 m (Day et al., 1996). Faults within the central block may be described as intrablock faults. These faults are typically short, discontinuous and have minor displacement (5 to 10 m) (Day et al., 1996). The largest intrablock fault, the Ghost Dance fault, has up to 25 m of displacement (Fig. 1). Other important intrablock faults include the Sundance fault, faults in the hanging-wall of the Bow Ridge fault (part of the “imbricate fault zone” of Scott, 1990), and the Drill Hole Wash fault (Fig. 1).

Concurrent geologic mapping activities in the central block at the surface and within the ESF have defined a number of areas where the correlation of structural features between the surface and the subsurface is almost one-to-one. Correlation is best for faults with a meter or more of apparent vertical separation, particularly within the Tiva Canyon Tuff, where uncertainties in surface-to-ESF projections are minimal (Sweetkind et al., 1996a). Along the North Ramp of the ESF, the numerous faults that cut Azreal Ridge (Fig. 1) have virtually the same expression in the surface and subsurface; the same number of faults are observed, with virtually the same amount of offset (Barr et al., 1996). There is similar excellent surface-to-subsurface correlation near the southern end of the Main Drift of the ESF, at the southern extension of the Ghost Dance fault (S. Beason, written communication, 1996). Both at the surface and in the ESF, 250 m below the surface, this portion of the Ghost Dance is a single, simple fault plane that dips steeply to the west with minor offset (1-2 m) (Day et al., 1996).

Numerous very small (less than 1-m offset) faults identified within the ESF are generally not resolvable at the surface due to lack of exposure or lack of suitable stratigraphic markers. Many small faults in the repository block (those with 1 to 10 m of displacement) are vertically and laterally discontinuous. Much of the minor displacement is accommodated by the fracture network, so that small faults need not be vertically continuous (Sweetkind et al., 1996b; Potter et al., 1996b). Offsets on the smaller faults are accomplished through distributed slip over broad zones, with the extension taken up in small amounts of slip over numerous joints. Strain between the discrete fault strands appears to be accommodated either by distributed brecciation, or by incremental movements along numerous pre-existing cooling joints (Sweetkind et al., 1996b; Potter et al., 1996b).

4.2. Synopsis of Structural Development

The major north-south block-bounding faults developed in response to regional east-west extension after eruption of the 12.8 Ma Topopah Springs Tuff (Day et al., 1996). Extension continued throughout the eruption of the 12.7 Ma Tiva Canyon Tuff. Evidence for the timing of fault motion includes growth-faulting relationships observed along a splay of the Solitario Canyon fault and at Busted Butte. At these locations, faults that cut the Topopah Spring Tuff die out upsection within nonwelded rocks that comprise the PTn hydrogeologic unit. Faulting at these locations is accompanied by apparent stratigraphic thickening of the rocks that comprise the PTn hydrogeologic unit (Day et al., 1996). The main phase of fault movement is bracketed by the 12.7-Ma Tiva Canyon Tuff and the 11.6-Ma Rainier Mesa Tuff, although in the central block area minor motion on the Solitario Canyon and Bow Ridge faults has continued through the Quaternary (Simonds et al., 1995).

Geometric relations between north- and northwest-striking faults in the vicinity of the central block are consistent with a kinematic model in which sinistral strike-slip sense of shear was accompanied by down-to-the-west dip-slip motion (O’Neill et al., 1992). Evidence for a kinematic model includes: 1) southwest-plunging slickenlines on the Solitario Canyon fault, indicating components both of left-lateral and down-to-the-west dip slip motion (Simonds et al., 1995); 2) west-side-down faults commonly step to the left along northwest-striking segments (for example, the Dune Wash fault, Day et al., 1996); and 3) narrow northwest-trending grabens that resemble tension gashes occupy stepover zones between overlapping (but discontinuous) north-trending faults (Potter et al., 1996a; Day et al., 1996). Clockwise vertical axis rigid body rotation of the structural blocks defined by the north-south block-bounding faults (O'Neill et al., 1992**;** Rosenbaum et al., 1991; Scott, 1990) may be the result of regional dextral shear associated with the northwest-striking Walker Lane tectonic belt (Hudson et al., 1994). Such clockwise rotation of north-south oriented structural blocks would cause a component of sinistral shear along the block-bounding normal faults (Day et al., 1996).

5. Description of the Fracture Network

Once a fast path is initiated near the surface, specific characteristics of the fracture network control its ability to sustain a fast component of flow to greater depths. Hence, conceptual models of fast paths within the flow system must be based on an understanding of the factors that control fracture intensity and connectivity within lithologic units, as well as fault/fracture continuity across units.

5.1. Cooling Joints and Tectonic Joints

The fracture network developed within the welded pyroclastic flows of the Paintbrush Group may be subdivided into cooling joints (joints interpreted to have formed as a result of tensional stresses related to the cooling of the flow) and tectonic joints (joints that result from regional extensional stresses) (Throckmorton and Verbeek, 1995). Each lithostratigraphic zone at Yucca Mountain has a characteristic suite of fracture attributes including: orientation distribution; intensity; trace length distribution; and predominance of joint type (Throckmorton and Verbeek, 1995; Sweetkind and Williams-Stroud, 1996). Depositional boundaries and variations in welding, devitrification and lithophysae development within the Paintbrush Group control fracture intensity and connectivity (Sweetkind and Williams-Stroud, 1995). The degree of welding has the greatest effect on the overall character of the fracture network. Fracture intensity and network connectivity within nonwelded and poorly welded units are much lower than in the surrounding welded units. Fracture intensity increases with degree of welding within the welded pyroclastic flows due to the presence of cooling joints and because increasing brittleness of the rock favors an increase in the number of tectonic joints. Termination percentage increases markedly in the welded portions of pyroclastic flows due to the presence of multiple joint sets and to the presence of cooling joints that typically have long trace lengths that act as important connectors of the network (Sweetkind and Williams-Stroud, 1996).

The development of lithophysae inhibits fracture propagation, resulting in decreases in joint length and continuity, and increases in surface roughness and trace irregularity (Sweetkind and Williams-Stroud, 1996). Fracture mapping within the upper lithophysal and middle non-lithophysal zones of the Topopah Spring Tuff at pavement P2001 at Fran Ridge highlights the differences in fracture character as a function of lithology (Sweetkind et al., 1995a). At pavement P2001, fractures within the middle non-lithophysal zone tend to be planar or arcuate with low surface roughness; fractures within the upper lithophysal zone are sub-planar but extremely rough. On average, fractures in the middle non-lithophysal zone are significantly longer than fractures in upper lithophysal zone. At pavement P2001, fracture intensity varies from a high of 1.7 m/m^2 in the middle non-lithophysal zone to a low of 0.54 m/m^2 in the upper lithophysal zone. These changes in fracture character occur abruptly at the lithologic contact (Sweetkind et al., 1995a). Similar abrupt changes in fracture characteristics are noted in the ESF at both the upper and lower contacts of the middle nonlithophysal zone of the Topopah Spring Tuff (S. Beason, written communication, 1996).

Cooling joints have been identified in every zone of the Tiva Canyon Tuff and Topopah Spring Tuff that are at least moderately welded (Throckmorton and Verbeek, 1995). Cooling joints are also present in the Pah Canyon Tuff and Yucca Mountain Tuff where these units are welded; cooling joints are absent in the non-welded PTn units (Sweetkind et al., 1995a). Cooling joints within the Topopah Spring and Tiva Canyon Tuffs often consist of two orthogonal sets that are steeply dipping, resulting in a rectangular pattern of joints (Barton, 1984; Barton et al., 1993). The joints of one set typically dominate in length and abundance over those of the other. Less frequently, a third, subhorizontal set of cooling joints is present. These joints are generally shallowly dipping surfaces that are subparallel to flattening foliation, have very long trace lengths (5 to 10 m) and gently undulate (Throckmorton and Verbeek, 1995). The shallowly dipping cooling joints are more common at particular stratigraphic intervals, for example, near the contact between the middle nonlithophysal and upper lithophysal zones of the Topopah Spring Tuff (Sweetkind et al., 1995b).

The fluid-flow properties of the fracture network within the Paintbrush Group are dependent upon the vertical continuity of the fracture network and the degree to which the fractures within each lithostratigraphic unit are interconnected. Fracture connectivity within the Paintbrush Group as a whole is limited by the Paintbrush Tuff nonwelded (PTn) hydrogeologic unit, an interval of nonwelded, bedded tuffs that has moderate to high porosity and permeability, largely stratabound fracture networks and very low fracture intensity (Moyer et al., 1996; Sweetkind et al., 1995a). Fracture connectivity within the welded portions of the pyroclastic flows within the Paintbrush Group is dependent on the degree of communication between fracture networks within individual zones. High effective permeabilities resulting from overall high fracture connectivity within the welded units at Yucca Mountain may be inferred from: 1) airflow in wells as a result of barometric and topographic effects (Weeks, 1987); 2) transient pneumatic pressure disturbances caused by the excavation of the ESF (J. Rousseau et al., written communication, 1995); and 3) pathways analysis of a simulated fracture network in the Tiva Canyon Tuff (Anna and Wallman, in press). However, because each lithostratigraphic zone has its own set of fracture attributes, each zone is unique in its ability to act as a flow path, resulting in a stratigraphic control of possible flow path geometry. For example, what may be a single feature in one part of the section (such as a fault in the PTn), may be a broad, diffuse flow pathway in another (e.g., a pathway composed of a series of interconnected cooling joints).

5.2. Syngenetic Brecciation

Breccias comprise a distinctive subset of the fracture system. Localized zones of intense rock breakage range in lateral extent from a few centimeters to several meters. Some, but not all, breccia zones are associated with discrete faults or faults of more than local extent (Levy et al., 1996). Breccias have played a complex role in enhancing the connectivity of fractures and faults that function collectively as fast paths for infiltration. In at least a few important cases, the genesis of fast pathways began with syngenetic fracturing and brecciation.

Breccia zones that began to form during the cooling of their host tuffs are present in all major units within the ESF. The syngenetic timing of rock breakage is documented by overgrowths of high-temperature and early deposited minerals on the breccia clasts. The criteria linking these secondary minerals to the post-depositional cooling period have been established by a combination of textural, isotopic, and geochronological studies (e.g., Carlos, 1985; Cowan et al., 1993; Levy, 1993; Whelan et al., 1996).

6. Concepts of Fast-Path Structure Development

Elevated $^{36}Cl/Cl$ values indicating a component of bomb-pulse ^{36}Cl are a fortuitous tracer that form the basis for identifying a connected fast pathway from the surface to the ESF. However, despite the variety of geologic data available, the nature of the pathway and connection between structural features is necessarily conjectural. Only portions of the pathway can be observed - those exposed at the surface and in the ESF. The rest of the path, including the connections between surface and ESF features, has to be described through geologic inference. In many cases, the possible pathway may be non-unique. It may be impossible to prove what the actual pathway was, but available geologic information may be used to describe the most likely pathway.

Sample locations in the North Ramp and Main Drift of the ESF that show evidence of bomb pulse ^{36}Cl were analyzed for structural significance through an integration of the following types of data: 1) observations of the local structural setting of each sample site; 2) mapped surface and subsurface structural features; and 3) fracture information from detailed line surveys in the ESF. Based on work to date using the above data, the primary controls on the distribution of bomb-pulse ^{36}Cl in the ESF, ranked by importance, are: 1) the presence of faults that cut the PTn hydrogeologic unit; 2) the magnitude of surface infiltration; and 3) structural features that result in lateral diversion of flow away from fault zones. Each of these controls is discussed below.

6*.1. Presence of Faults that cut the PTn Hydrogeologic Unit*

The most important structural control seems to be the simple presence of faults that create breaks in the PTn. Sample locations in the north ramp and main drift of the ESF that show evidence of bomb-pulse ^{36}Cl are located in the general vicinity of faults mapped at the surface (Fabryka-Martin et al., in press). A tabulation of all of the faults in the ESF with more than about 3 m offset (Table I) shows that, with a few exceptions, the samples from these faults contain a component of bomb-pulse ^{36}Cl. Most of the sampled faults had bomb-pulse ^{36}Cl along the fault plane; two exceptions are the southwestern splay of the Drill Hole Wash structure and the Ghost Dance fault at the southern end of the main drift (Table I).

TABLE I
Fault Attributes in the ESF

Fault Name	ESF Station (R. Rib)	Amount of Offset	Fault Orientation		Offset Sense	$^{36}Cl/Cl$ ratio x 10^{-15} (from Appendix B)	LANL ID
			Strike	Dip			
Bow Ridge	2+00	100 m	N 10° E	70° W	Normal, down to west	2452 2424 2382 2132 722 381	E009-2 E011-2 E012-2 E008-2 E010-2 E243-1
--	4+36	7 m	N 2° W	68° E	Normal, down to east	Not sampled	--
--	5+43 to 5+55	7.5 m	N 9° W (approx.)	72° E (approx.)	Normal, down to west	Not sampled	--
--	6+11 to 6+17	3 to 4 m	N 4° W	73° W	Reverse, down to east	Not sampled	--
--	7+04	13 m	N 11° E	79° W	Normal, down to west	Not sampled	--
--	7+41	5 m	N 2° W	78° W	Normal, down to west	Not sampled	--
--	8+44	2.5 m	N 29° E	86° W	Normal, down to west	530	E245-1
--	11+14 to 11+28	12 m	N 10° W	85° W	Normal, down to west	Not sampled	--
--	11+51 to 11+79	18 m	N 29° E	86° W	Normal, down to west	633	E251-1
Drill Hole Wash, NE splay	19+02 to 19+43	4 m	N 29° E	86° W	Normal, down to west; unknown strike-slip component	3023 1838 1144 2290	E042-2 E042-3 E043-2 E044-2
Drill Hole Wash, SW splay	22+71	2 m	N 00° E	72° W	Normal, down to west; unknown strike-slip component	863	E046-1
--	24+40	1.5 m	N 20° W	80° W	Normal, down to west	2579	E050-2
Sundance	35+93	Minor?	N 25° W	84° E	Normal, down to east; unknown strike-slip component	2840 1674	E175-1 E175-3
Ghost Dance	57+27	3 m	N 25° E	90°	Normal, down to west	483	E253-1

Bomb-pulse values are associated with a variety of fault types, including: 1) a block-bounding fault (Bow Ridge fault); a probable strike-slip fault (Drill Hole Wash fault); and smaller, intrablock faults (Sundance fault). There does not appear to be any association between the presence or absence of bomb-pulse ^{36}Cl and type of fault, orientation of fault, or the amount of offset along the fault. The critical characteristic is that the fault is large enough to break the PTn. This observation is consistent with the results of hydrologic modeling of percolation through the PTn hydrologic unit. Model results required enhanced fracturing of the PTn to allow the arrival of at least a small amount of water with the bomb-pulse signature at the middle nonlithophysal zone of the Topopah Spring Tuff (main drift of the ESF) in 40 years or less (Fabryka-Martin et al., in press).

In some instances, the projected locations of bomb-pulse samples in the ESF do not appear to correspond to a fault mapped at the surface, yet the high $^{36}Cl/Cl$ may nonetheless indicate the likely existence of a fault that cuts the PTn hydrogeologic unit. Two examples are sample sites located under Diabolus Ridge (Fig. 6); neither sample site is obviously associated with a fault mapped at the surface. Across the central part of Diabolus Ridge, a gently east-dipping reverse fault is mapped at the surface with about 7 m of offset at the level of the upper portion of the Tiva Canyon Tuff (Day et al., 1996; see Fig. 6). This fault was observed in the upper part of drill hole USW SD-9, located in the wash immediately south of Diabolus Ridge (Fig. 6), where the fault cuts poorly welded Yucca Mountain Tuff (Engstrom and Rautman, 1996). Projected downward, this fault cuts the base of the PTn hydrologic unit almost directly above the bomb-pulse sample location at Sta. 26+79 (Fig. 6). Although other pathways may exist, the simplest explanation for the presence of bomb-pulse ^{36}Cl at this site is that the fast pathway includes the fault that cuts the PTn hydrogeologic unit above the sample location. At a nearby sample site (Sta. 24+40) a fault with 1.5 to 2 m of offset cuts the upper lithophysal zone of the Topopah Spring Tuff (Barr et al., 1996). No corresponding fault is mapped at the surface (Day et al., 1996). Although it is unknown how far upsection the Sta. 24+40 fault extends, it does not offset the lower lithophysal zone of the Tiva Canyon Tuff at the surface (Day et al., 1996). There are several examples of mapped faults that can be documented to be pre-Tiva Canyon Tuff in age because fault displacement dies out within the PTn hydrologic unit or within the lower portions of the Tiva Canyon Tuff (Day et al., 1996). The fault at Sta. 24+40 may be such a pre-Tiva Canyon Tuff fault. A reasonable interpretation of this fault, in the light of the ^{36}Cl results, is that it offsets the base of the PTn hydrologic unit.

6.2. Magnitude of Surface Infiltration

Based on preliminary data, there appears to be a correlation between the ^{36}Cl signature of a particular fault zone and the fault's surface location with respect to spatially distributed infiltration (Flint and Flint, 1994, 1995; Flint et al., in press). In the main drift of the ESF, faults containing a component of bomb-pulse ^{36}Cl tend to have surface traces located within areas of high infiltration, as defined by Flint et al. (in press). For example, both the Sundance fault and the fault on Diabolus Ridge are relatively minor features at the surface, with trace lengths less than one kilometer and cumulative vertical displacements of 10 m or less. Yet the surface traces of both faults intersect fractured bedrock on topographically high ridge tops that are free of alluvial cover, all of which serve to enhance infiltration (Flint and Flint, 1994; Flint et al., in press). In contrast, faults without elevated $^{36}Cl/Cl$ values have surface traces that tend to coincide with areas of low infiltration (Flint et al., in press). For example, where the surface traces of the southwestern splay of the Drill Hole Wash fault and the southern part of the Ghost Dance fault overlie the ESF, the faults are exposed in topographically low wash bottoms or side slopes with thick alluvial material, conditions associated with low levels of infiltration (Flint and Flint, 1994; Flint et al., in press). Based on these few examples, it appears that the surface intersection of relatively minor faults with zones of high infiltration is conducive to fast flow, whereas faults of equal or greater displacement that intersect zones of low infiltration do not have elevated $^{36}Cl/Cl$ values at the ESF level.

Further evaluation of the interplay between structural features and spatially distributed infiltration will be made when $^{36}Cl/Cl$ data are available from additional samples from faults that are currently being processed, including: 1) North Ramp faults that are also exposed on the surface on Azreal Ridge, 2) the Dune Wash fault and other large faults intersected by the South Ramp of the ESF.

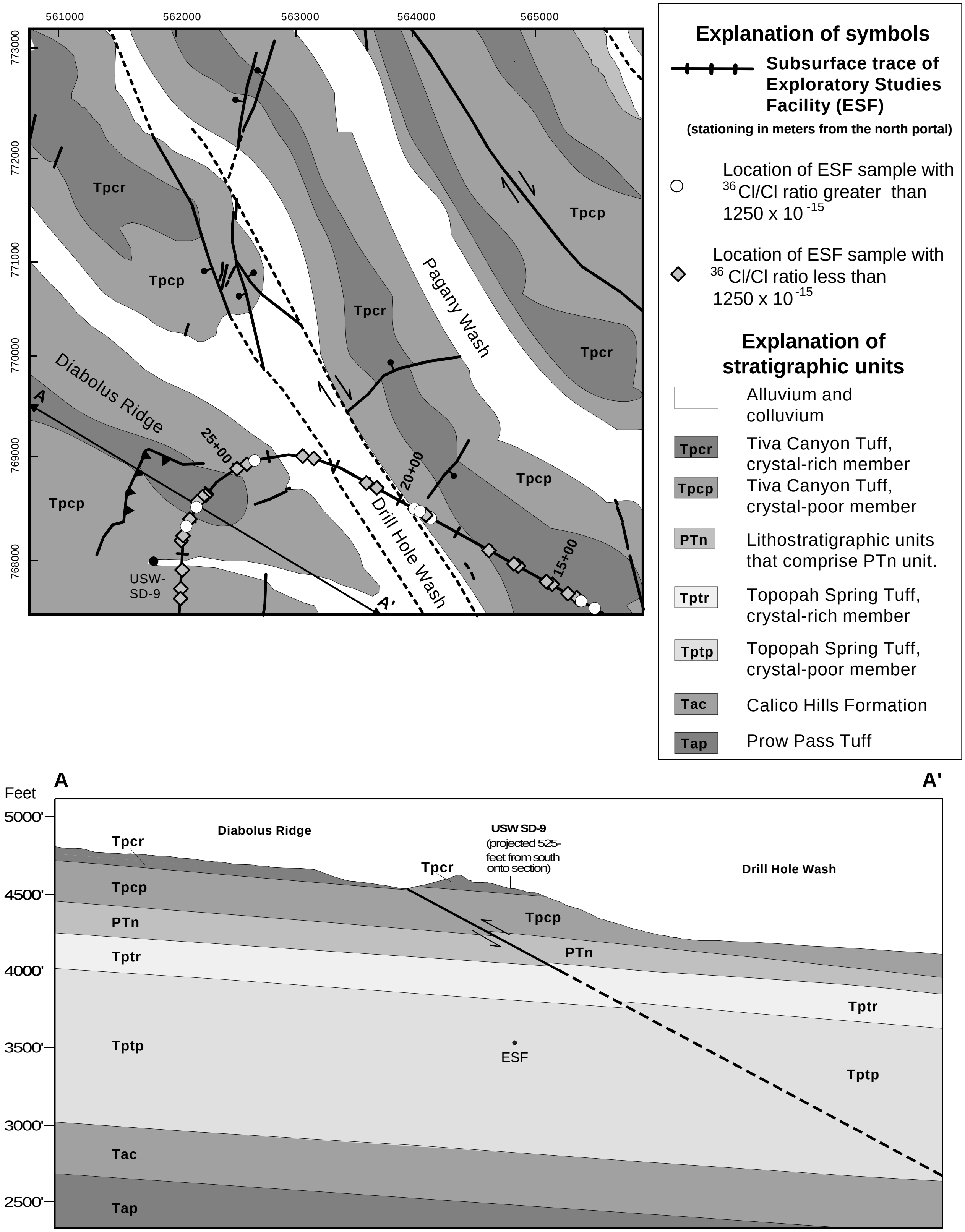

Figure 6. Geologic map and cross section of Drill Hole Wash vicinity (surface geology after Day et al., 1996). Map coordinates are Nevada State Plane coordinates, in feet.

6.3. Structural Features that Result in Lateral Diversion of Flow Away from Fault Zones

A number of the bomb-pulse sample localities along the north ramp of the ESF are tightly grouped in the vicinity of a single fault or individual joint. In contrast, bomb-pulse localities in the general vicinity of the Sundance fault comprise a 300-m zone along the ESF (Fabryka-Martin et al., in press)(Fig. 7). The Sundance fault is the only structure mapped in this vicinity (Potter et al., 1995; Day et al., 1996) that could serve as the pathway through the PTn hydrogeologic unit. The broad zone of elevated $^{36}Cl/Cl$ values north of the fault thus represents lateral diversion of flow away from the plane of the fault. Such lateral diversion implies a connection between the fault and other structures, either small subsidiary faults or interconnected joints, in the rock mass surrounding the fault.

A connected pathway through a joint network is most likely where joints are long, where fracture intensity is high, and where fracture intersections are plentiful. Larger fractures have greater chances of intersecting, and there is a much higher probability of forming a connected pathway from a small number of intersecting long fractures than from a large number of short fractures (Odling, 1995). Also, the likelihood of fracture interaction increases as both fracture intensity and the number of fracture intersections increase (LaPointe and Hudson, 1985). In the vicinity of the Sundance fault in the ESF, the locations of connected fracture pathways are governed by the difference in fracture character of various lithostratigraphic zones and spatial restrictions of cooling joints.

The upper lithophysal zone of the Topopah Spring Tuff does not have a well-connected fracture network. Fracture data collected by detailed line surveys in the ESF show a roughly four-fold increase in the fracture spacing (in fractures per ten meter interval) between the upper lithophysal and middle nonlithophysal zones (Fig. 8a). Similar differences in fracture intensity between these two lithostratigraphic zones were observed in detailed mapping of the P2001 pavement at Fran Ridge (Sweetkind et al., 1995b) and through statistical analysis of simulated fracture networks of these zones (Anna, in press). Fractures are generally longer within the middle nonlithophysal zone than in the upper lithophysal zone. In the ESF, the average fracture trace length increases from around 1 m in the upper lithophysal zone to nearly 2 m in the middle nonlithophysal zone and the number of very long fractures (greater than 10 m) is much higher in the middle nonlithophysal zone (Fig. 8b). Mapping at the P2001 pavement reveals that the large joints in the middle nonlithophysal zone of the Topopah Spring Tuff are a network of cooling joints, upon which a number of generations of shorter tectonic joints were superimposed (Sweetkind et al., 1995b). Large, gently dipping cooling joints are common in the stratigraphic interval surrounding the contact between the upper lithophysal and middle nonlithophysal zones. These joints, well exposed at pavement P2001 (Sweetkind et al., 1995b) and common in ESF exposures of the middle nonlithophysal zone (D. Barr, U.S. Bureau of Reclamation, written communication, 1997), are subparallel to the flattening foliation and could act as important connectors between steeply dipping cooling joints that receive infiltration input from a fault.

The Sundance fault is the first fault exposed in the ESF at the level of the middle nonlithophysal zone of the Topopah Spring Tuff. Lateral diversion of flow away from the Sundance fault is very unlikely within the upper lithophysal zone of the Topopah Spring Tuff, which has a poorly connected fracture network and few throughgoing discontinuities (Sweetkind et al., 1995b; Anna, in press). Lateral diversion of flow below the level of the PTn hydrogeologic unit is most likely within the middle nonlithophysal zone of the Topopah Spring Tuff where large, relatively closely spaced cooling joints and the common presence of gently dipping cooling joints promote network connectivity and the chances of a connected pathway in the rock mass surrounding the fault.

At the surface, the Sundance fault zone has up to 10 m of aggregate dip-slip separation (Potter et al., 1995). However, at certain stratigraphic levels the fault displacement is manifested as the summation of numerous 1- to 2-m contact offsets along small, discontinuous, discrete fault segments (Potter et al., 1995). This distributed style of deformation is interpreted to be the result of the accommodation of extensional strain through distributed slip along many reactivated joints (Potter et al., 1996b; Sweetkind et al., 1996b). Potter et al. (1995) related the stratigraphically controlled faulting style along the Sundance fault to the relative frequency of cooling joints in various lithostratigraphic zones of the Tiva Canyon Tuff, with broader areas of deformation occurring in lithostratigraphic zones where cooling joints were more numerous. Such a deformational style in the Topopah Spring Tuff would favor broad, distributed deformation within the middle nonlithophysal zone and would only accentuate the differences in the network properties within the Topopah Spring Tuff described above.

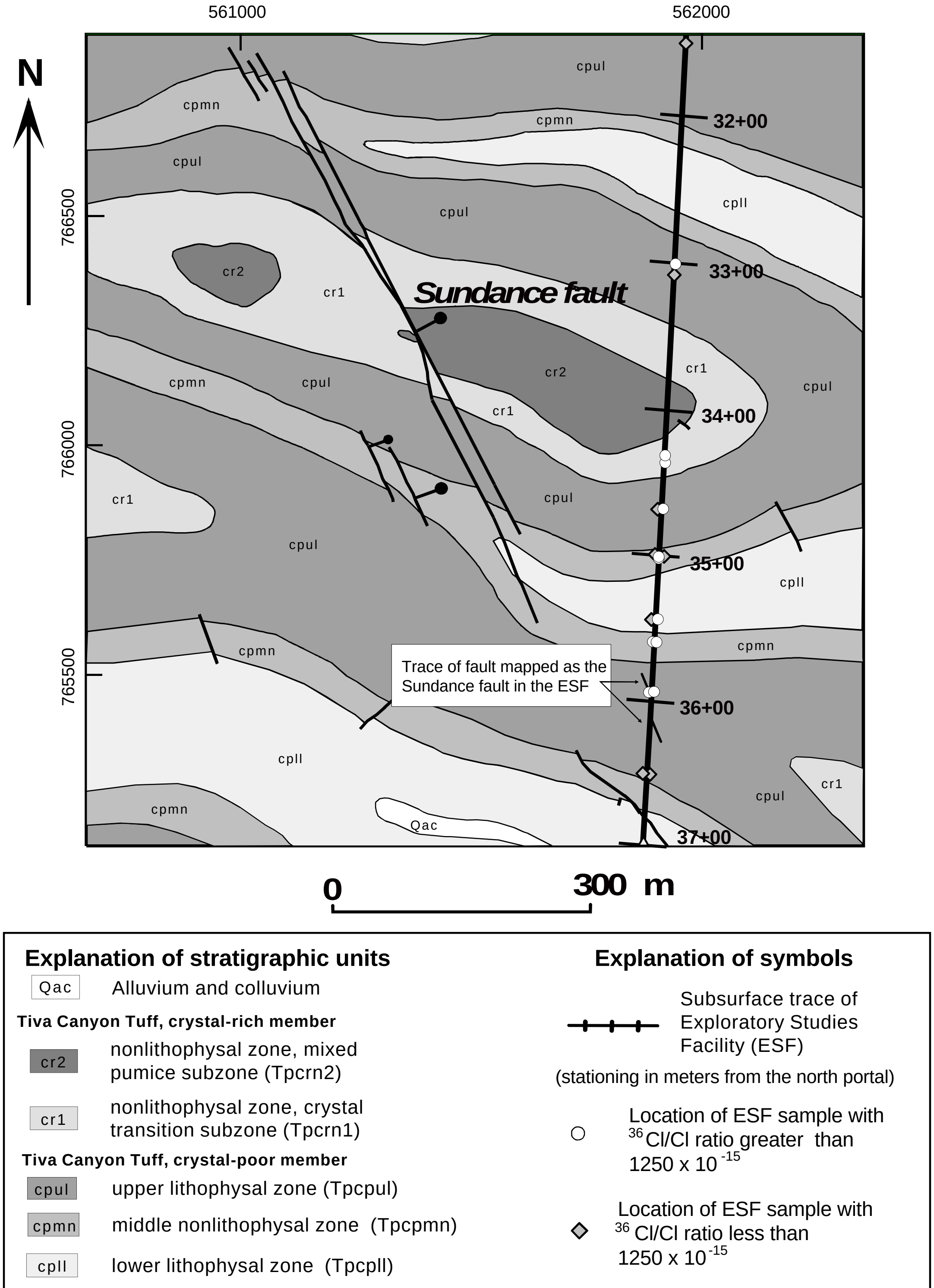

Figure 7. Geologic map of the Sundance fault (after Potter et al., 1995), with the projected trace of the Exploratory Studies Facility (ESF). The location of the fault mapped as the Sundance fault in the ESF is shown. Map coordinates are Nevada State Plane coordinates, in feet.

Figure 8(a).

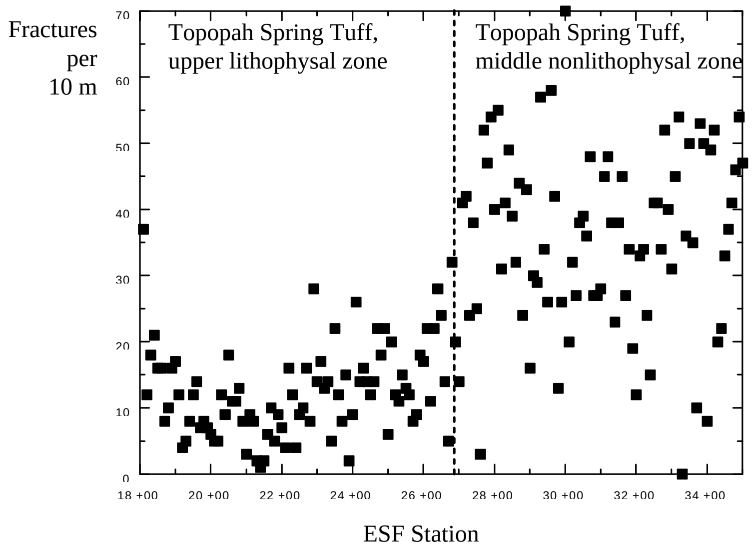

Figure 8(b).

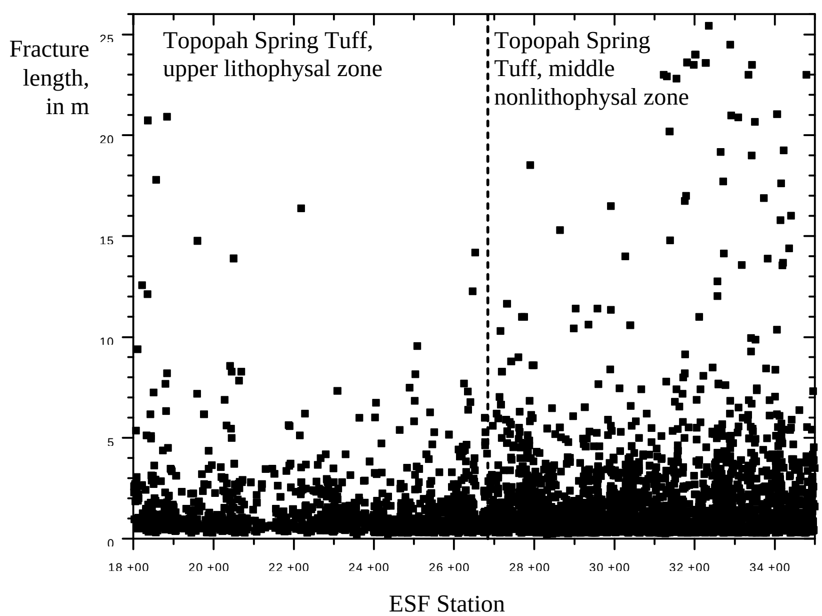

Figure 8a-b. Comparison of fracture characteristics of the upper lithophysal and middle nonlithophysal zones of the Topopah Spring Tuff. Data are from detailed line surveys in the ESF (Albin et al., 1997). ESF stations are marked in 100 m increments.